MARTIAN ATMOSPHERIC EFFECTS ON RADIO WAVE PROPAGATION

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Because Mars has very low atmospheric pressure (less than 1% of Earth's), the Martian atmospheric radio refractivity is about two orders of magnitude smaller than that of Earth. Ray bending effect on microwave is not obvious. The optical depths of Martian clouds and fogs are about 1.0 at visual wavelengths. In the limiting case, the Martian clouds are expected to be similar to terrestrial high-level cirrus clouds. The total attenuation due to Martian clouds, fog and aerosols should be less than 0.3 dB at Ka-band. Dust storms in Mars can significantly affect a communication link. **A** large dust storm can cause at least a 3-dB loss at Ka-band. Most large storms occur in the southern hemisphere during later spring and early summer. The Martian atmospheric gaseous attenuation at Ka-band is less than 1 dB due to very low concentrations of gaseous H20 and O_2. Martian gaseous absorption is at least three orders of magnitude lower than at Earth. Radio noise emissions at Mars are'mainly from its atmospheric emission and surface noise. For a downward-looking antenna, the total noise temperature is about the same as the Earth's for all frequency bands of interest. For an upward looking antenna, the **sky** noise temperature is the highest at UHF (about **55** K) and lowest at **X-** and Ka-band (about **5** K). The sky noise temperature, however, **is** only a small part the total receiving-system noise temperature, which is dominated by receiver thermal noise.

1. Martian Atmospheric (Tropospheric) Refractivity and Cloud Optical Depths

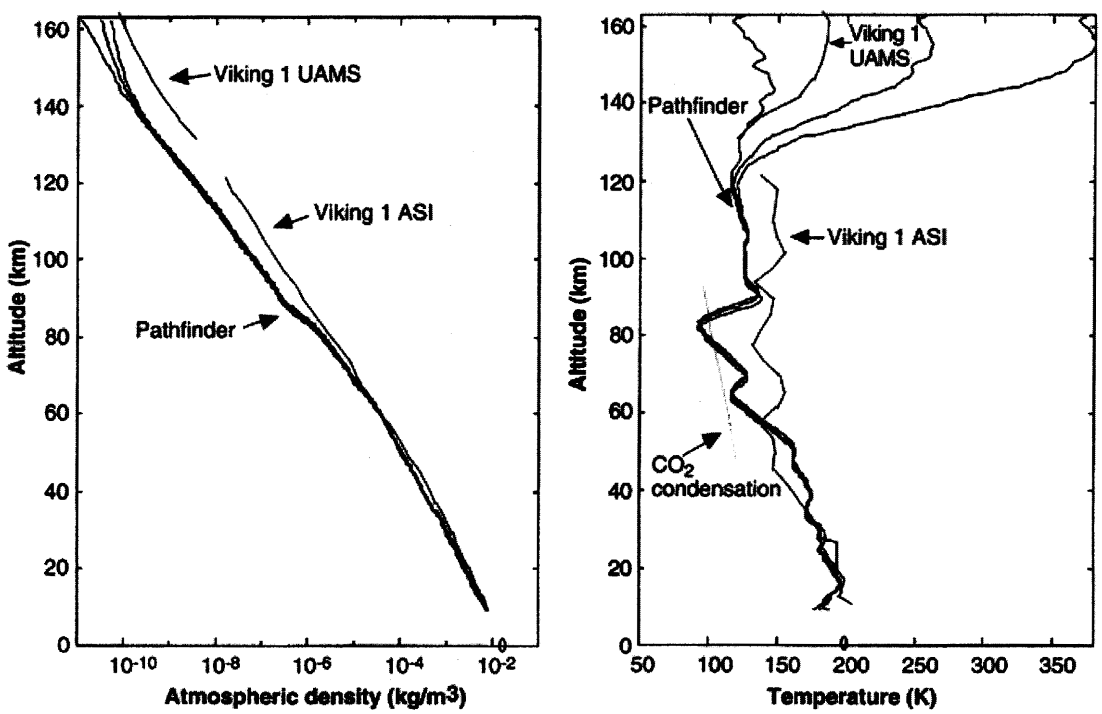
Based on measurements of Martian atmospheric pressure and temperature, calculated refractivity profile can be fitted using a function

$$N(h) = N_0 \exp(-h / H_N)$$

where N_0 (**3.9** N unit) is the surface value of N when altitude h = 0, and H_N (11.0 km) is the refractivity scale height. The refractive index of the Martian troposphere at the surface is about two orders of magnitude smaller than that of Earth. Even though the Martian tropospheric radio refractivity has a small value, it can still cause ray bending and multipath effects. Only when the wave angle is very close (φ **< 0.3)** to the horizontal, can the wave ray be trapped by a horizontal duct. Because Mars is only about half the size of Earth and because Mars has a larger surface curvature than Earth, it is expected that the signals reflected at Mars surface will have a greater defocussing loss. Tropospheric scintillation caused by the refraction index variation fluctuations in Martian troposphere should be only about 0.5% **of** that in the Earth atmosphere, if temperature fluctuation is the same for Mars and Earth.

Midlatitude Martian Atmospheric Model

$$\frac{p}{p_0} = \exp\left[-\frac{\mu}{R}\int_{z_0}^{z}\frac{g(z)}{T(z)}dz\right]$$



(Left) The atmospheric density profiles derived from the Mars Pathfinder accelerometer data. Results from the VL-1 atmospheric structure instrument **(ASI)** and the Viking 1 upper atmosphere mass spectrometer **(UAMS)** are also plotted for comparison. (Right) The atmospheric temperature profiles derived from the Pathfinder measurements and from the VL-1 **ASI, UAMS** experiments, and the CO_2 condensation. The surface density and temperature measured by the Pathfinder **MET** instrument (oval) are also shown.

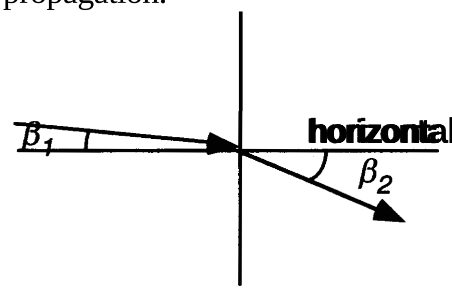
Radio Refractivity:

$$N = (n-1)\times 10^6 = 77.6P/T \ (N \text{ unit})$$

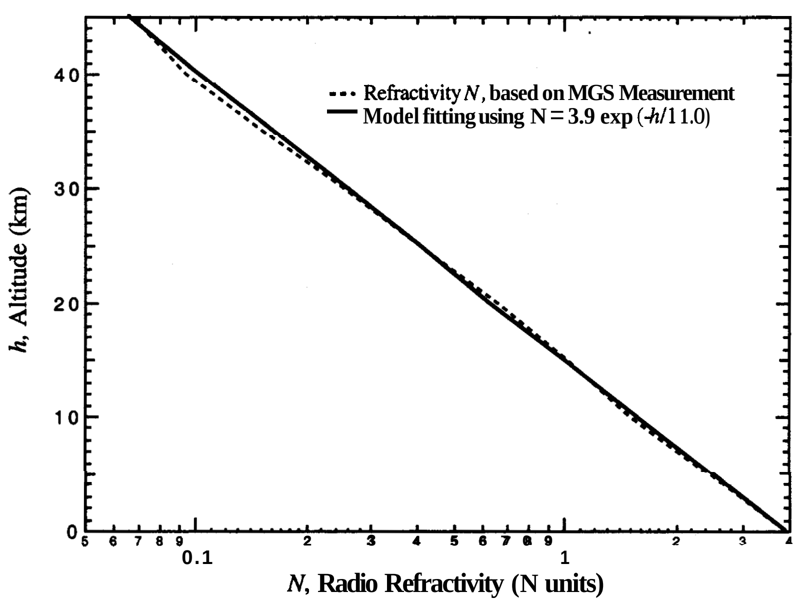
where n **is** refractive index. Ray bending curvature C

$$C = -\frac{1}{n}\frac{dn}{dh}\cos\beta \approx -\frac{dn}{dh} = -\frac{dN}{dh}$$

for low elevation angle (β) propagation.



A cartoon showing how low elevation angle incident wave is bended.



Radio refractivity for Martian atmosphere. Dry **air pressure and temperature profiles are used for** the **refractivity calculation.**

Martian Clouds and Fogs:

Although not as pronounced as on Earth, clouds are a common feature on Mars. The Martian atmosphere has only a trace of water vapor; however, the temperature and pressure are such that the atmosphere is usually close to saturation and produces clouds. Even fiom Earth-based telescopes, clouds have been observed by transient brightening on the surface of Mars. Numerous cloud patterns have been seen from the Mariner and Viking spacecraft and have been classified into various categories. The optical depths **of** Martian clouds and fogs are small (**~ 1.0** at visual wavelengths). Ice depolarization effects due to Martian clouds on radio waves are still unknown, but they are expected to be small because of the lower optical depth and the thinner cloud layer. Attenuation due to clouds and fog depends largely on their water contents. ***So*** far we have little knowledge because direct cloud measurements are not yet available. However, Martian clouds are expected to have relatively less water liquid content because the clouds have a small optical depth. Martian aerosol attenuation effect on radio wave propagation is smaller than that of the Martian clouds **.**

In general, the Martian atmospheric environment is quite good for optical communications because of its thinner atmosphere, except during dust storms because the optical depth of Martian clouds is only one fifth of Earth clouds. Martian aerosols can cause some attenuation to laser beams; however, this effect is very small compared with that of aerosols at Earth.

Optical Depths of Clouds and Fogs on Earth and Mars* (at Visual Wavelengths)

Atmospheric Condition	Earth		Mars	
	Optical Depth	Distribution	Optical Depth	Distribution
Clouds H_2O	~5	50% coverage	–1.0	Winter polar; behind high places
Clouds CO_2	None	None coverage	–0.001 –1.0	Many places Winter polar
Fog	~3	Many places places	-0.2 –1.0	Morning Valleys & crater bottoms
Aerosol Dust	To be provided	To be provided	0.5	Everywhere
Dust Storms	To be provided	To be provided	10.0	Southern Hemisphere or global

***Adapted from Annis [1987]**

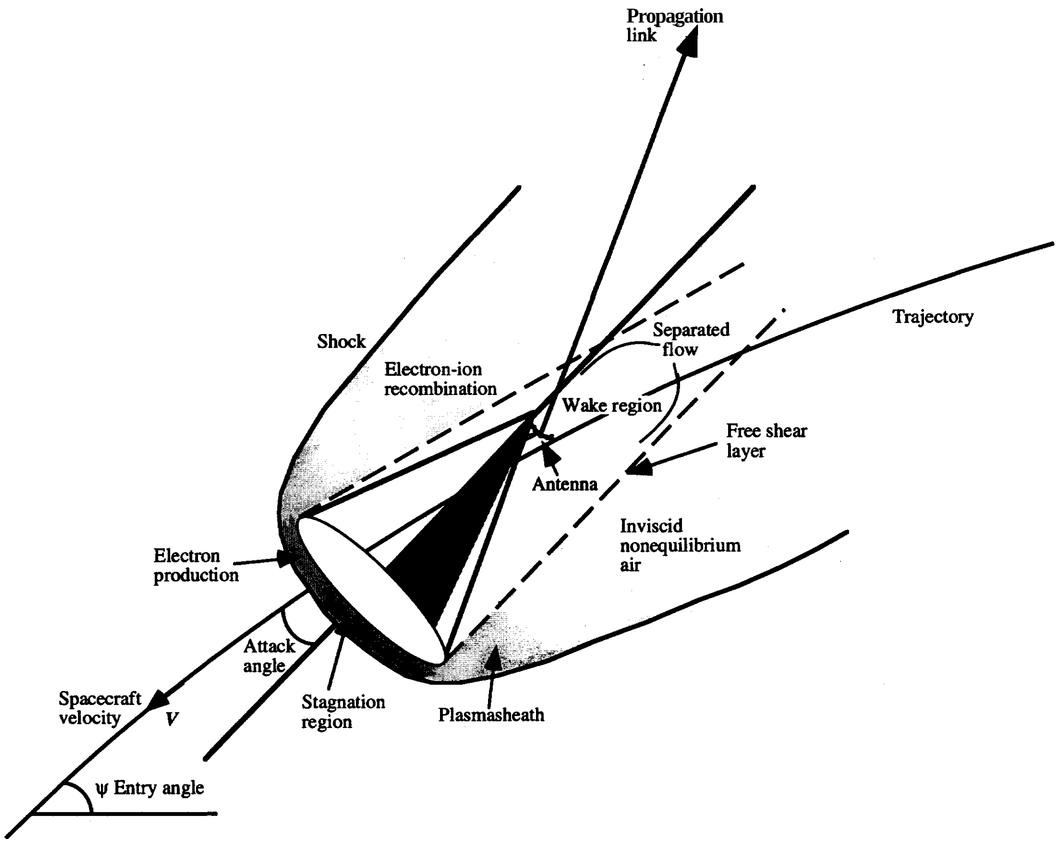
2. Communication Blackout during Martian Atmosphere Entry Phase

During spacecraft atmospheric entry, signal transmissions will be significantly degraded (blackout). **A** 30-second communication disruption at X-band occurred during Mars Pathfinder decent was probably caused by plasmasheath blackout. The main cause of blackout is reflection or absorption of electromagnetic wave energy at all communication frequencies (f) lower than the local plasma frequency (f_p), where f_p **(MHz)** = 9.0 x 10^{-3} $N^{1/2}$ (cm^{-3}). For $f < f_p$ a plasma behaves like **a** conductor, while for $f > f_p$ the plasma is practically transparent. The critical plasma densities for various frequencies of signals from UHF to Ka band are listed below.

Critical Plasma Densities and Communication Frequencies

Signal Frequency	UHF 381 MHz	S-band 2.295 GHz	X-band 8.43 GHz	Ka-band 32 GHz
Plasma Density	1.8×10^{9} cm^{-3}	6.5×10^{10} cm^{-3}	8.8×10^{11} cm^{-3}	1.27×10^{13} cm^{-3}

Using this computer program and an isothermal Martian atmospheric density profile and assuming the lander has an entry speed of **8.1** km/s, the electron density in the wake was found with a peak value **of** about 3×10^{12} **cm^{-3}**. This density is higher than critical density for X-band communication and leads to a **10.2** sec communication blackout. **A** denser atmosphere will generate a longer blackout duration. Two basic directions for reduction of the problem are indicated: (1) Increase the signal frequency to a point where its value is higher than the plasma frequency value (i.e., Ka band); **(2)** Reduce the plasma electron density by modifying the plasma.

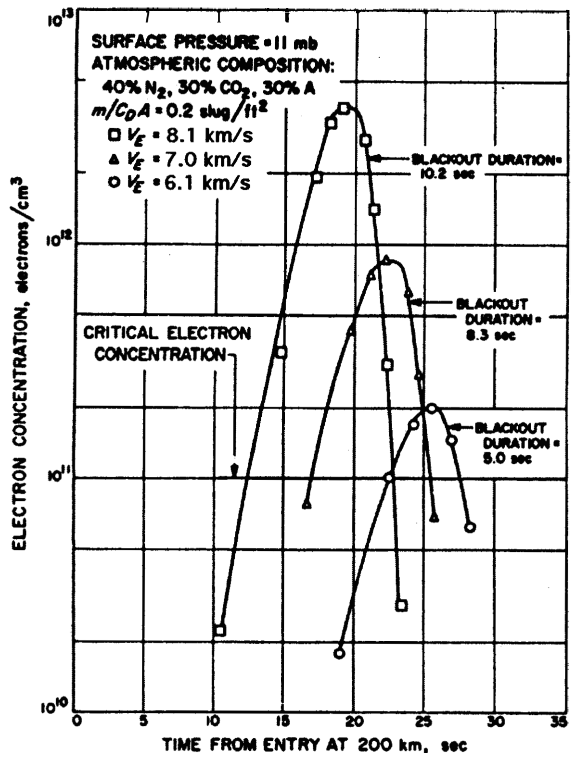


Diagrammed view of a blunt hypersonic spacecraft entering the Martian atmosphere. A plasmasheath generated around the capsule blacks out the communication signals.

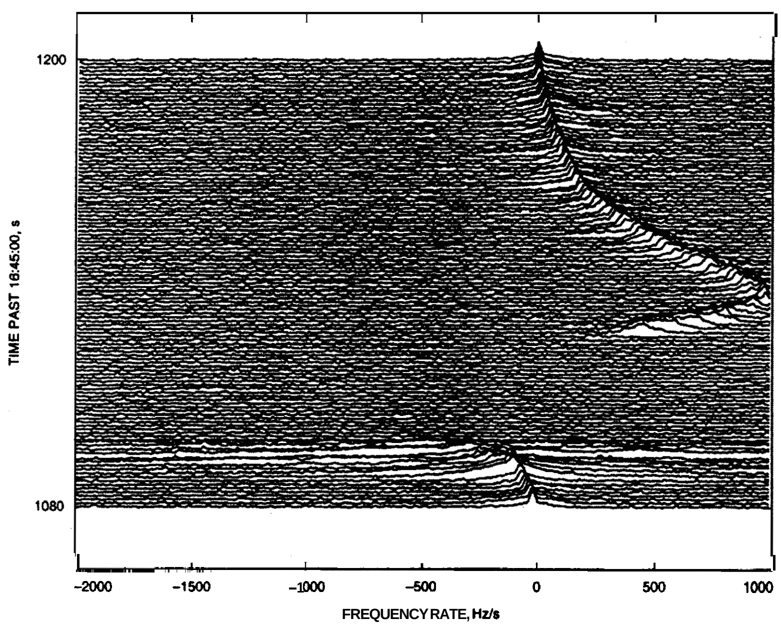
Electron density caused by atmospheric impacting ionization for a shock velocity between 4.0 and 9.0 km/s at stagnation and at the wake region of the capsule.

$$n_{e,s} = 1.5 \times 10^{10} \rho^{0.95} V^{11.8} \qquad \text{at stagnation point}$$

$$n_{e,s} = 1.83 \times 10^{9} \rho^{0.95} V^{10.37} \qquad \text{at wake region}$$



Electron densities in the capsule wake region vs. time from entry for various entry velocities and for entry angle, ψ_E=90°.



Tracking signals during Mars Pathfinder atmospheric entry phase. The plot shows the Doppler frequency peak ramp rate (i.e., signal derivative) **vs.** time for the *peak* deceleration event. There was a **30-s** signal outage beginning at **17:03:20 UTC (1100** sec past **16:45:00) (from** Wood et al., **1998).**

3. Martian Atmospheric Gaseous Absorption

Because the Mars troposphere consists of almost entirely dry air and the surface atmospheric water content is 3000 times lower than at Earth, the water absorption peaks in the spectrum are very low. Thus, the windows that on Earth are bounded by water lines become much wider. From *60* GHz to 300 GHz there is almost no attenuation. This feature is obviously in contrast to the Earth's situation, in which heavy rain and water vapor dominate the attenuation. The Martian atmosphere is dominated by CO_2 and N_2 gases. Under normal conditions, they do not have electric or magnetic dipoles, ***so*** they do not absorb electromagnetic energy. However, they may generate dipoles through collision and interaction with waves under a high density condition. We often see that both gases have many absorption lines in the infrared and visible bands in the Earth atmosphere. In this calculation, we have used an average surface value (300 ppm) for Martian water vapor, instead of a maximum value (400 ppm), which corresponds to the worst case. An accurate calculation for zenith opacity requires information about scale heights of H_2O and O_2. The ratio of total zenith absorption in the Earth atmosphere relative to Mars should be equal to the ratio of column number densities of H_2O and O_2 of Earth relative to Mars. Actually, the exact amount of gaseous H_2O is still debatable.

Martian Atmospheric Parameters:

Surface Pressure: –6.1 mb (variable)

Surface Density: –0.020 kg/m^3

Scale height: ~ 11.1 km

Average temperature: –210 K

Diurnal temperature range: 184 K to 242 K

Mean molecular weight: 43.34 g/mole

Atmospheric composition (by volume):

Major: Carbon Dioxide (CO_2) - 95.32% ; Nitrogen (N_2) - 2.7%

Argon (Ar) - 1.6%; Oxygen *(O,)*- 0.13%; Carbon Monoxide (CO) - 0.08%

Minor (units in ppm): Water vapor (H_2O) - ~150-300 (variable);

Nitrogen Oxide (NO) - 100; Neon (Ne) - 2.5;

Hydrogen-Deuterium-Oxygen (HDO) - 0.85; Krypton (Kr) - **0.3;**

Xenon (Xe) - 0.08, Ozone **(O,)**- 0.04 - 0.2.

where ppm **is** part(s) per million.

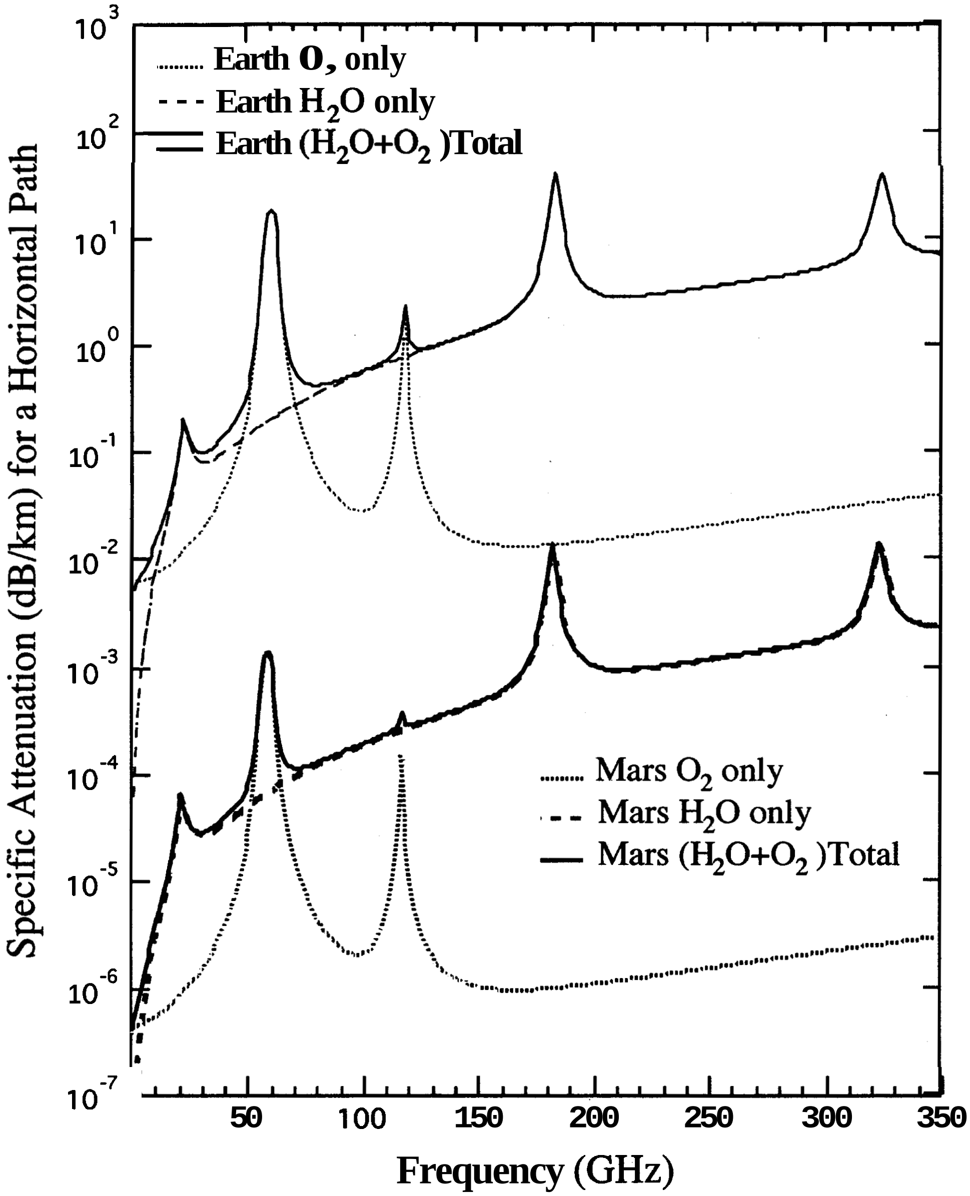
Surface Atmospheric Parameters at Mars and Earth

Planet	P, pressure (mb)	T, temperature (K)	M, mean molecule weight	ρ, mass density (kg/m3)	N, number density (m^{-3})	V_m, mole volume (m^3/kmole)	H, scale height (km)
Mars	6.1	210	43.34 g/mole	0.021	2.85×10^{23}	2.1×10^{3}	–11.1
Earth	1013	300	28.61 g/mole	1.29	2.7×10^{25}	22	–9.5

Ratios of Atmospheric Compositions between Earth and Mars

Ratios (Earth/Mars)	CO_2	N_2	Ar	O_2	CO	H_2O
for F_i (fraction by volume)	4.2×10^{-4}	28.9	0.58	161	2.4x1'0	33.3
for β_i (fraction by weight)	6.4×10^{-4}	44	0.88	244	3.9×10^{-4}	50.4
for ρ_i and n_i (density)	0.04	2704	54	1.4×10^{4}	0.024	3068

Gaseous Absorption at Surfaces of Earth and Mars

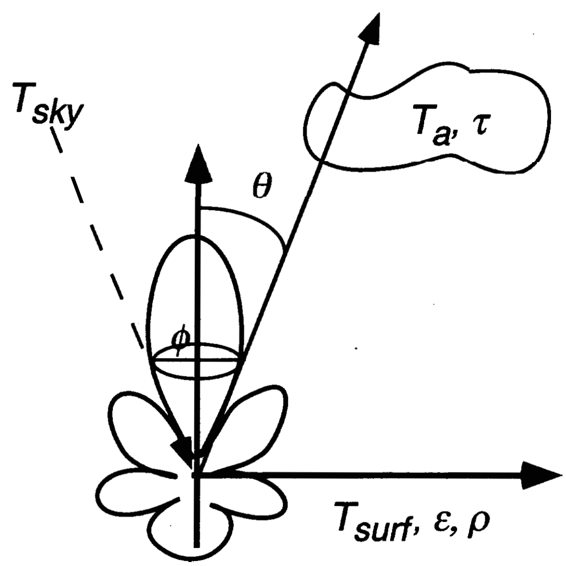


Gaseous specific absorption attenuation by water vapor, oxygen, and **both at the surface of** Earth **and Mars. The upper three thin lines are for attenuation at** Earth, **while lower three thick lines are for Mars.**

4. Mars Background Noise Temperature Seen by Receiver Antenna

Radio noise emissions at Mars basically include three types of sources: Martian atmospheric emission, noise from Martian surface, and extra-Martian sources. In the same time when the Martian atmosphere has a gaseous attenuation through the absorption by O_2 and water vapor, hydrometeors, and aerosols, These matters also radiate the noise almost in the same frequency. Martian surface emissivity is closely related to its surface physical temperature. Below the 1 GHz, the noise is mainly dominated by galactic source. Actual radio noise temperature received by an antenna is strongly dependent on antenna's pointing, elevation angle, and gain pattern. Using newly developed Martian atmospheric gaseous attenuation model, different antenna patterns (beam antenna and omnidirectional antenna), we have calculated the background noise temperature for various view angles. The brightness temperature received by an upward and downward-looking antenna is also tabulated below.

Mars Background Noise Temperature Seen by Receiver Antenna



Radio emission seen by an upward-looking beam antenna. Antenna temperature is an integration effect of background brightness temperature over antenna gain in all direction.

$$T_r = \frac{\int\limits_{mainlobe} G_r(\theta)T_B(\theta)d\Omega + \int\limits_{sidebeam} G_r(\theta)T_B(\theta)d\Omega}{\int\limits_{\Omega} G_r(\theta)d\Omega}$$

where $\int\limits_{\Omega} d\Omega = \int_0^{\theta}\int_0^{2\pi} \sin\theta d\theta d\phi$

where ***T,:*** received noise average temperature;

G,: receiver antenna pattern;

T_B: brightness temperature;

$d\Omega$: solid angle (all solid angle $\int d\Omega = 4\pi$);

θ: polar angle;

ϕ: azimuth angle (2π).

Background Temperatures for Two Special Antenna Pointings:

1. Downward-looking Antenna:

$$T_{B_d} = \varepsilon T_s e^{-\tau} + T_a(1-e^{-\tau})$$

2. Upward-looking Antenna:

$$T_{B_u} = T_{sky} e^{-\tau} + T_a(1-e-')$$

where:

ε: Surface emissivity, a function **of** view angle and frequency ($0 \le \varepsilon \le 1$), also depending on surface soil type, roughness, dielectric constant, moisture, etc.;

T_s: Surface physical temperature **(210** K on Mars; 300 K on Earth);

τ: Atmosphere optical depth, **a** function **of** wave frequency, depending on cloud, gaseous absorption, etc. **A** transparent object has a very small z, where $\tau = A(f)$ dB/4.34.

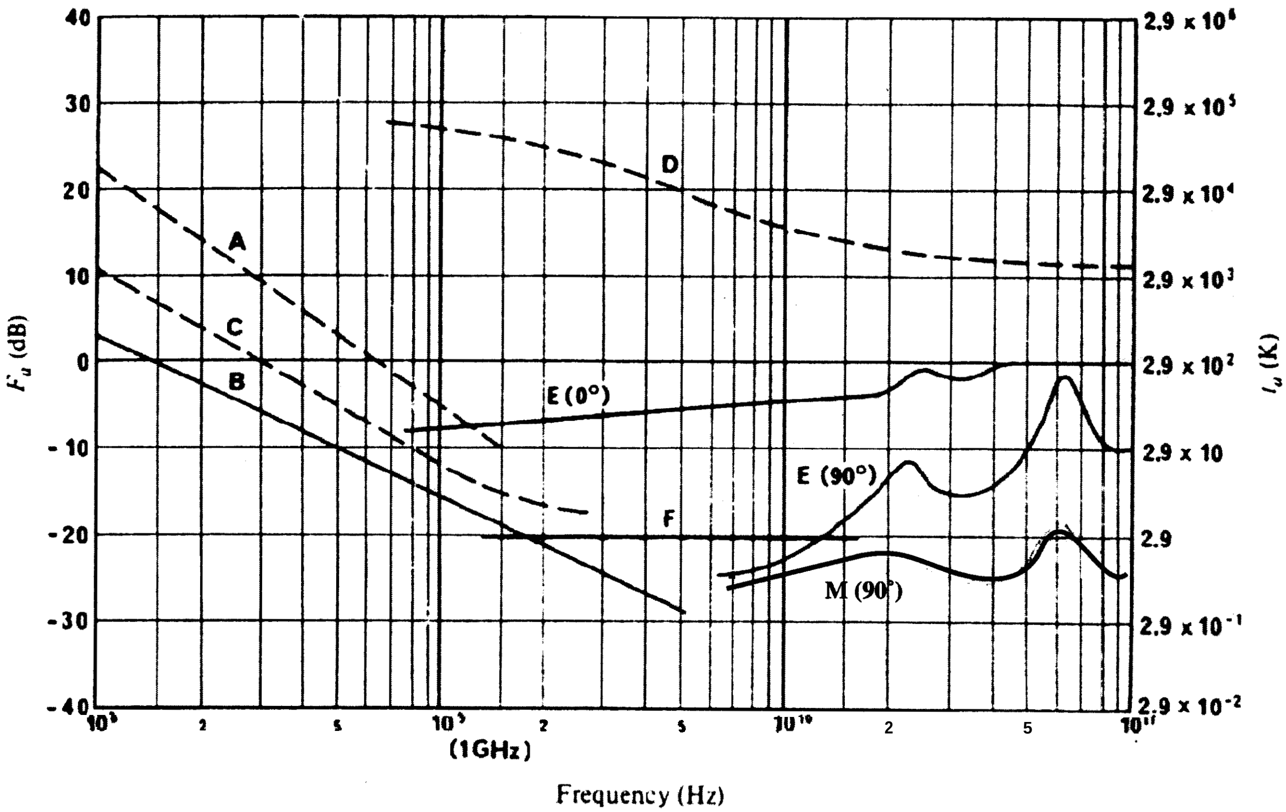
T_a: Atmospheric temperature at one scale height (200 K on **Mars,** 220 K on Earth);

T_{sky}: Sky temperature as a function **of** wave frequency;

p: Surface reflectivity ($\varepsilon+\rho=1$).

Antenna Maximum and Minimum Gains for Different Frequency Bands

	UHF band	S-band	X-band	Ka-band	Omni-directional
f (GHz)	0.4	2.3	8.4	32	
λ(cm)	75	13	3.6	0.94	
D/d	1.3	7.7	27.7	106	
G_{max}(dB)	12	25.4	36	47	3
G_{min}(dB)	-3.6	-7.4	-10.2	-13	-1



External noise figure F_a (in dB) and antenna temperature t_a (K) versus frequency.

Optical depth due to Atmospheric Gaseous Absorption

$$e^{-\tau} = e^{-A(f)dB/4.34} = 10^{-A(f)dB/10}$$

$$\tau = A(f)dB | 14.34$$

where $A(''$ is one-way vertical gaseous attenuation

$A(f) =$ [redacted] $, z)dz = \kappa_g(f,z)H_g$

where κ_g is specific attenuation (dB/km) and H_g **is** scale height of absorption gases.

Parameter Values and Ranges on Mars and Earth

	Mars	Earth
&	0.86-0.97	0.40-0.85
ρ	0.03-0.13	0.15-0.60
T_s	210 (184-242) **K**	300 (210-320) **K**
T_A	200 **K**	220 K
τ	0.001-1.0 5.0 (for duststorm)	0.1-5.0
H_g	11.1 km	9.5 km

ε: Surface emissivity, Mars values were obtained from Earth-based Radar observations in frequency ranges from **UHF** to Ka bands.

ρ: Surface reflectivity ($\varepsilon + \rho = 1$).

T_s: Surface physical temperature (210 **K** on Mars; 300 **K** on Earth);

T_a: Atmospheric temperature at one scale height (200 **K** on Mars, 220 **K on** Earth);

τ: Atmosphere optical depth, a function of wave frequency, depending on cloud, gaseous absorption, etc. **A** transparent object has a very small τ.

Brightness Temperature (in Kelvin) for Different Antenna Pointing

		UHF	S band	X band	Ka band
Emissivity	Mars	0.9	0.91	0.92	0.93
&	Earth	0.6	0.62	0.64	0.68
Reflectivity	Mars	0.1	0.09	0.08	0.07
ρ	Earth	0.4	0.38	0.36	0.32
One-way attenuation	Mars	0.4x 10''	$0.8x10^{-4}$	$1.2x10^{-4}$	$3.0x10^{-4}$
$A(f)$ dB	Earth	0.2	0.4	0.6	2.5
Optical depth	Mars	$0.1x10^{-4}$	$0.2x10^{-4}$	$0.3x10^{-4}$	$0.7x10^{-4}$
τ	Earth	0.05	0.09	0.14	0.58
Sky Brightness	Mars	29	2.9	2.9	2.9
Temperature T_{sky}	Earth	29	2.9	2.9	20
Downward	Mars	189	191	193	195
Looking T_{Bd}	Earth	182	188	196	210
Upward	Mars	29	2.9	2.9	2.9
Looking T_{Bu}	Earth	40	22	32	117

Antenna Temperature (in Kelvin) for Various Antenna Pointing and Frequency Bands at Both Mars and Earth

		UHF	*S* band	X band	Ka band	Omnidir
Downward	Mars	155	**185**	191	193	
looking	Earth	150	180	193	210	
Upward	Mars	54	**9**	4	3	79
looking	Earth	**88**	27	32	117	**85**
Receiver Thermal Temperature		462	462	462	462	462

5. Mars Dust Storm and its Effects on Propagation

The Mars wind can frequently generate large dust storms. This happens especially during late spring or early summer seasons for the southern Martian hemisphere, when Mars is at its perihelion. **For** a normal dust storm, the attenuation is about 1 dB. At the worst situation, Martian dust storms have a 3 dB attenuation on Ka-band radio wave. Lower frequency signals will suffer significant less loss. The attenuation depends largely on dust mass loading, dust size distribution, etc. Currently we still have little information about these factors. When the spacecraft lands in the southern hemisphere, at least a 3-dB margin should be considered for lander and rover communication.

Local and Regional Dust Storms:

A local dust storm observed by Mariner **9** at the edge **of** the south polar ice cap, just visible at the lower right. The time is that **of** perihelion, $L_s = 250°$.

A local dust storm in the Solis Planum region at **Ls** = 227°. The season is midsouthern spring, between the two 1977 global storms.

Martian Dust Storm Attenuation

$$A(\lambda) = 54.62 \frac{r\tau}{\lambda} \left[\frac{3\varepsilon''}{(\varepsilon' + 2)^2 + \varepsilon''^2} \right]$$

$$A(\lambda) = \frac{1.029 \times 10^6 \varepsilon''}{\lambda [(\varepsilon' + 2)^2 + \varepsilon''^2]} N_T \bar{r}^3$$

where $A(\lambda)$ is in dB/km, r **is** particle radius **in** meter, and λ is wavelength in meter, τ is the optical depth.

Dielectric Permittivity Index of Dust Particles

Index ε	10 GHz*	10 GHz Clay	10 GHz Sand	S band**	32 GHz Clay***	8.8 GHz Clay***	Dust at 20µm***	Dust at 2 µm***
ε'	4.56 (+0.11, -0.24)	7.42 (+1.73, -1.22)	3.35 (±0.03)	4.56	2.5	2.5	2.0	3.0
ε''	2.51 (+0.074, -0.066)	1.119 (+0.597, -0.437)	0.042 (±0.02)	0.251	**0.06**	0.02	0.4	0.1

* Ghobrial [1980]
** Goldhirsh [1982]
*** **Smith and Flock** [1986]

A Comparison of Dust Storm Parameters between Earth and Mars

	N_T m^{-3}	ρ g/m^3	Mean Size (μm)	Maximum Size (μm)	Visibility (m)	Path Length	Attenuation at 32 GHz	Mass Loading
Earth	10^8	$2.6x10^6$	30-40	80-300	5.1-3.8	10km	65 dB	40-60 g/m^3
Mars	$3x10^7$	$3.0x10^6$	1-10	20	184	10km	3 dB	0.4 g/m^3

6. Summary

Because both Earth and Mars have ionosphere and atmospheres, radio waves suffer some losses in additional to the free space loss which has a range from 277 dB (for minimum distance) to 294 dB (for maximum distance) between Mars and Earth. At Earth, for 99% of the time, weather conditions are such that the total tropospheric attenuation for Ka band is about 5 dB for vertical propagation. This loss includes gaseous absorption, rain and cloud scattering, etc. Among these losses, the dominant loss is due to rain scattering and absorption, about 3 - 4 dB under normal conditions. At Mars, the dominant attenuation factor is dust storms. For a worst-case (large mass loading), attenuation can be 3 dB or higher at Ka band. However, this type of storm rarely occurs. Dust storms mostly occur in the southern hemisphere during spring/summer seasons. Under normal conditions, a storm can cause at most about a **1** dB loss.

At Mars no rain observation has been reported yet. Even though it is possible to have rain, the rain would be ***so*** light that it would not cause any significant attenuation to radio waves. It is estimated that total tropospheric losses, including gaseous attenuation, cloud, fog, and tropospheric scattering (scintillation and turbulence), etc., are about 0.4 dB at Ka band. Thus, under normal conditions, the attenuation combined from a dust storm and the troposphere is about 1.4 to **2** dB, for a vertically propagating wave (compared with about 5 dB at Earth). The total attenuation will be about 3.4 dB for the worst case.

The Martian ionosphere will have some absorption and scintillation effects on VHF wave transmission just as the Earth's ionosphere does. At Earth, these losses are about 3.0 to 10 dB for at **127** MHz. At Mars, this type of loss will be much smaller, because the Martian ionosphere is one order of magnitude thinner than Earth's.

Another important attenuation factor for Martian surface communication is multipath due to reflections from rocks and canyon walls. Because there have been no experiments yet to measure these parameters on Mars., we can extrapolate from Earth-based experiments. We do not expect that there are any big differences in attenuation between rocks at Mars and Earth. In Earth's canyon and hilly environments, for **870** MHz waves, attenuation has a range of **2-7** dB, while for L band **(1.7 GHz),** the attenuation is **2-8** dB. At higher frequency, higher loss should be expected. Thus, surface rock attenuation is a potentially a large attenuation source on Mars.

For surface-to-surface propagation, we **do** not know what the actual loss is because there is no any rock attenuation experimental data yet. The total propagation loss between Mars and Earth is free-space loss, plus about a 8-dB atmospheric loss from both planets.

Finally, based on the Martian atmospheric environment, we strongly recommend using optical links for future Mars communications. Because of the thinner Martian atmosphere and the almost transparent Martian clouds, optical communication is almost perfect for links between Mars orbiters, between orbiters and landers, and even between Mars surface robots. Laser beams in the Martian atmosphere will have much less attenuation relative to those used in the Earth environment. We also suggest using low frequency (4.0 MHz) radio waves for Martian surface communication because the Martian ionosphere can effectively reflect these waves forward to areas beyond the line of sight. This will make Martian surface global communication possible.

Acknowledgements

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